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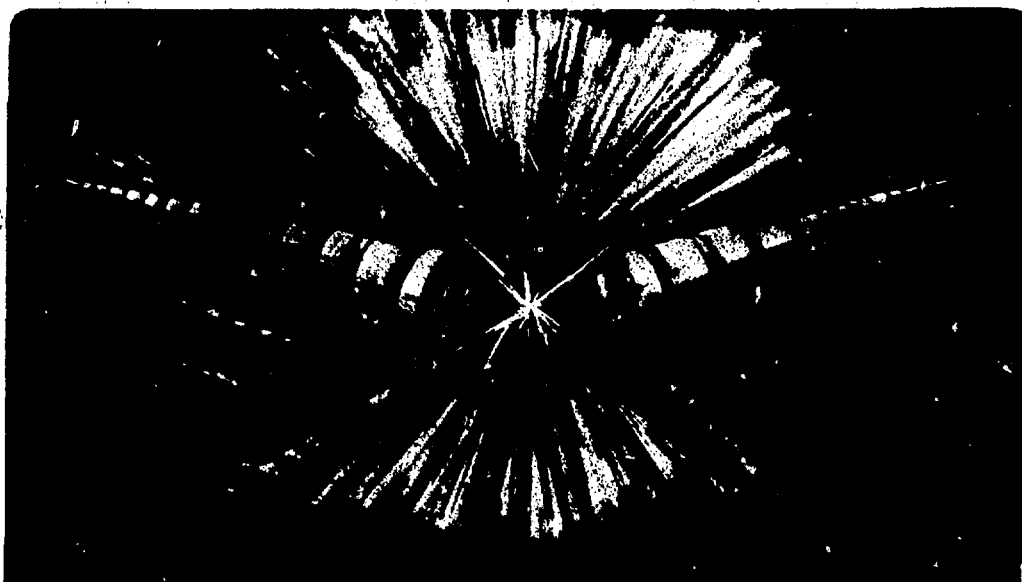
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**SINGLE PARTICLE DYNAMICS IN THE LBL 1-2 GeV
SYNCHROTRON RADIATION SOURCE IN THE PRESENCE
OF MAGNETIC IMPERFECTIONS, MAGNET DISPLACEMENT
ERRORS AND INSERTION DEVICES**

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March 1987



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SINGLE PARTICLE DYNAMICS IN THE LBL 1-2 GeV SYNCHROTRON RADIATION SOURCE IN THE PRESENCE OF MAGNETIC IMPERFECTIONS, MAGNET DISPLACEMENT ERRORS AND INSERTION DEVICES*

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1. Introduction

It is well known that introduction of nonlinear magnetic elements into a storage ring results in a limit in stable betatron motion at an amplitude that defines the "dynamic aperture". In electron storage rings designed for high brightness synchrotron radiation, like the LBL 1-2 GeV Synchrotron Radiation Source [1], the dominant nonlinear effects come from the strong sextupole fields that are required for chromatic correction. The dynamic aperture arising from this source of nonlinearity is described in an accompanying paper at this Conference [2]. In this paper we investigate the effects arising from other sources of perturbing fields that can be reasonably predicted in advance of construction. These are: field errors (both systematic and random) introduced through magnet design and finite construction tolerances; a random quadrupole component arising from a finite closed orbit distortion in the sextupoles; and the intrinsic focusing and nonlinear fields associated with the insertion devices.

2. Magnetic Field Errors

Multipole components in the iron dominated magnets that comprise the magnet lattice arise because their poles have finite widths, and because of construction tolerances. The former constraint leads to systematic components (the same in each magnet type) which have the same symmetry and orientation as the magnet in which they are found. These are known as "normal" components. Field errors that arise from construction tolerances are random in nature and can be either normal or "skew", i.e., of an orientation about the beam that is different from the normal component. To estimate the magnitude of these components for the magnets of the LBL Light Source, we have looked at the results achieved in existing magnets. These data have been extracted from documentation on machines that members of the LBL team are familiar with, namely, PEP (SLAC), SPS (CERN), and SRS (Daresbury, UK). The values used in our simulation are conservative when compared with these data.

Initially the code DIMAT was used to estimate the effects arising from the multipole components. The results were later confirmed using RACETRACK. In DIMAT the multipole expansion is expressed as:

$$B_y(x) = B_0 \sum_n k_n x^n / n!$$

Table 1. Magnet Multipole Errors

	$k_1 l$	$k_2 l$	$k_3 l$	$k_4 l$	$k_5 l$	$k_6 l$
Systematic:						
Dipoles	0.0	0.05	0.0	10^3	0.0	0.0
Quadrupoles	0.0	0.0	0.0	0.0	1.5×10^5	1.5×10^{12}
Random/Normal						
Dipoles	0.7×10^{-3}	0.1	15.0	100	0.0	0.0
Quadrupoles	1.0×10^{-3}	0.1 ^a	15.0	300	3×10^4	5×10^{11}

Skew:

Quadrupoles rotated about axis with rms skew = 0.5 mrad.

Sextupoles rotated about axis with rms skew = 1.0 mrad.

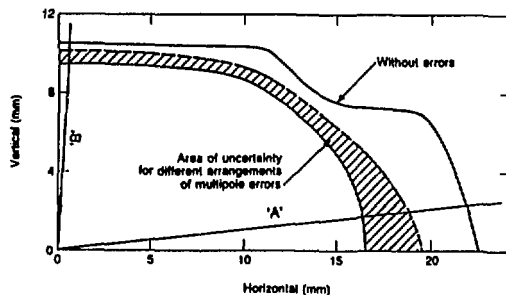
^aA random component from sextupoles included.

Table 1 shows the input values used in the simulation and Fig. 1 shows the effects on the dynamic aperture. It is seen that the main effect of the errors is felt in the radial plane, where the aperture is reduced from 22 mm to between 16 and 20 mm. The variation reflects the different distributions of random multipole components in the simulations.

We also tested the sensitivity to a particular multipole component (say, the random octupole field in the quadrupole magnets) by simply switching that component off. In this manner, we were able to ascertain that the most harmful component is the normal random quadrupole term. That this is the case is not surprising, but, it immediately points to another problem. That is, with the very strong sextupoles required for chromatic correction, a closed orbit error of 0.1 mm rms in the sextupoles gives rise to a random quadrupole component that is about twice that expected in the main lattice magnets! This is addressed in the next section.

3. Closed Orbit Distortion and Correction

Closed orbit distortions (COD) are generated by magnet displacement errors (bend, quadrupole and sextupole), bend magnet field errors, and bend magnet tilt errors. We have developed an algorithm to minimize the COD using the most effective corrector (mef) method and the local bump method. The orbit is sampled at 96 monitor stations around



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Fig. 1. Dynamic aperture in the presence of multipole errors. The significance of lines A & B is described in Section 3.

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the circumference and correction is applied via 72 correctors in the horizontal plane, and 48 in the vertical plane. In estimating the initial COD, we have taken alignment tolerances and field errors that are typical of modern accelerators:

magnet displacement errors (dx, dy) 0.15 mm rms,
dipole field errors ($\Delta B/B$) 1.5×10^{-3} rms, and
magnet rotation errors ($d\theta$) 0.5 mrad rms.

When correcting the orbit we assume a monitor alignment error of 0.1 mm rms. A typical closed orbit before and after correction is shown in Fig. 2. The harmonic distribution as the correction scheme proceeds is shown in Fig. 3, and the residual closed orbit for 20 different sets of random errors is shown in Fig. 4.

In order to assess the effect of the residual closed orbit in the sextupoles, we searched for the dynamic aperture of each different machine along the two lines marked "A" and "B" in Fig. 1. The result is plotted in Fig. 5, where "horizontal" refers to the projection of the dynamic aperture found along line A onto the horizontal axis, and "vertical" to the projection along B onto the vertical axis. In some cases the COD iteration was terminated before the minimum COD was achieved in order to give some depth to the abscissa. The reduction in dynamic aperture compared with that due to multipole errors (shown in Fig. 1) is clear.

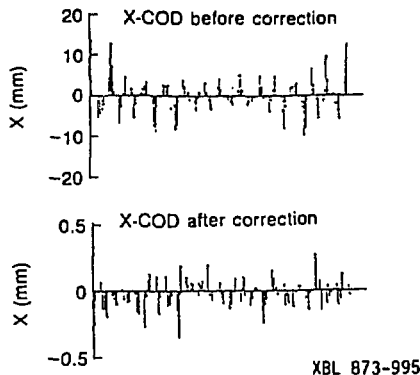


Fig. 2. Horizontal closed orbit distortion for one set of random errors, before and after correction.

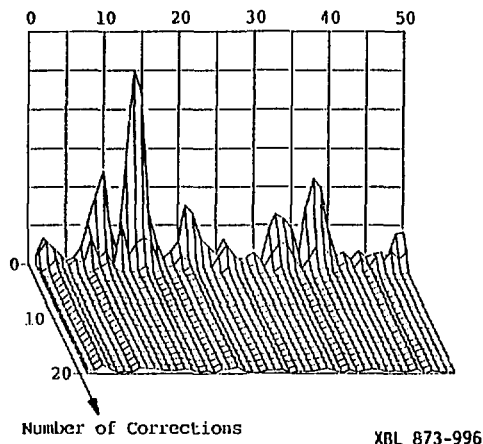


Fig. 3. Harmonic distribution of horizontal COD.

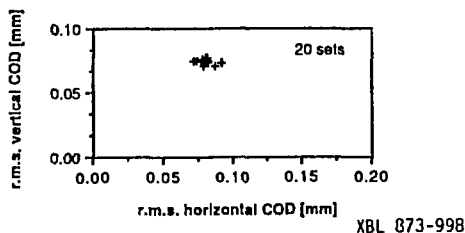


Fig. 4. Residual COD after correction.

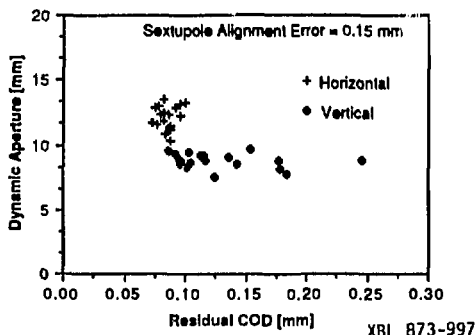


Fig. 5. Dynamic aperture vs. residual COD.

Again we have used the ability to "switch off" different errors to assess how this situation might be improved. We find that the misalignment error of the sextupole plays a dominant role in reducing the dynamic aperture. This is because the misalignment errors increase the net random quadrupole component. Thus, in operation, it will be necessary to first survey the sextupoles as accurately as possible, and then steer the electron beam through their magnetic centers.

4. Wigglers and Undulators

The LBL Light Source will be the first storage ring of its kind to have a large fraction of its circumference (about one-third) occupied by insertion devices. These devices are intrinsically nonlinear and will also provide focusing in one or both transverse planes, thus disrupting the periodicity of the ring. In this section we investigate the effects of these devices on the dynamic aperture. We assume that there is no closed orbit distortion and that the only sources of nonlinearity are due to the sextupoles and the insertion devices themselves.

The undulator field used in this simulation is that which provides a single peak in its radiation spectrum [3]:

$$B_y(x, y, z) = B_0 \cosh k_x x \cdot \cosh k_y y \cdot \cos k_z z$$

$$B_x(x, y, z) = \frac{k_x}{k_y} B_0 \sinh k_x x \cdot \sinh k_y y \cdot \cos k_z z$$

$$B_z(x, y, z) = -\frac{k}{k_y} B_0 \cosh k_x x \cdot \sinh k_y y \cdot \sin k_z z$$

where

$$k_x^2 + k_y^2 = k_z^2 = \left(\frac{2\pi}{\lambda_u}\right)^2, \quad \lambda_u = \text{undulator period.}$$

We have simulated the effects on the dynamic aperture of each of the five devices currently scheduled for initial operation of the Light Source (see Ref. 1 for details of the proposed wiggler and undulators) and have concluded that they are not too dissimilar. Here we present the results from the study of just one device, known as undulator U9.0. The parameters of this undulator are given in Table 2.

Table 2. Main Parameters of Undulator U9.0

Length [m]	4.8
Undulator period [cm]	9.0
Number of periods	53
Maximum peak field [T]	1.15
Gap [mm]	20.90
Maximum K-value	9.64

The principal effect of the undulator is to change the vertical betatron tune. For U9.0, $\Delta\nu_y = 0.042$. This "extra" focusing element can be matched into the lattice using the quadrupole pairs adjacent to the device. The tune shift is then accommodated by adjusting the quadrupoles in the remaining insertion regions. The result is a "matched insertion." We then find the dynamic aperture by tracking test electrons through the lattice elements, and through the undulator field described above. For this analysis, the magnet was sliced into ten segments per undulator period, with the nonlinear terms averaged over each slice. The resulting dynamic aperture is shown in Fig. 6, as curve A. As we mentioned above this dramatic effect can arise from two sources, namely, breaking of the superperiodicity and from nonlinear fields. In order to see whether either of these effects dominate the observed reduction in aperture, we have tracked the lattice with an imaginary "thick" element that provides focusing in the vertical plane only, with a strength equivalent to that of U9.0. The result is curve B in Fig. 6. It can be seen that the effects arising from symmetry breaking and from the nonlinear fields are about the same.

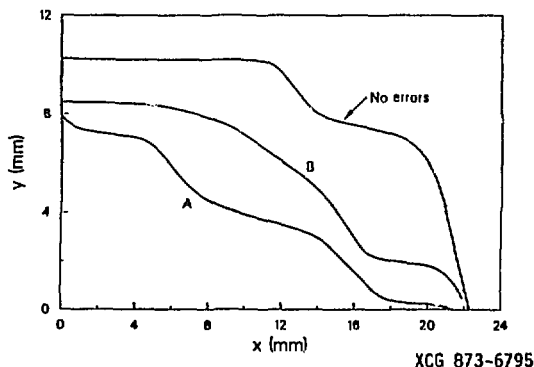


Fig. 6. Dynamic aperture. Curve A with undulator U9.0. Curve B with "linear element".

When more devices are included, the dynamic aperture shrinks further and it becomes progressively more difficult to tune the machine, since eventually the same quadrupoles are required to both match and tune. One solution to this dichotomy is simply not to match the insertions. We have looked at the dynamic aperture with either 1 or 4 symmetrically-placed insertions in the Light Source, with and without matching. The results are shown in Fig. 7. For this arrangement of insertions at least, it seems that the matched structure is worse than the unmatched structure! This result is encouraging, since trying to match 11 insertion devices, that are continually being tuned by the users, whilst maintaining both insertion matching and betatron tunes, may prove to be rather difficult.

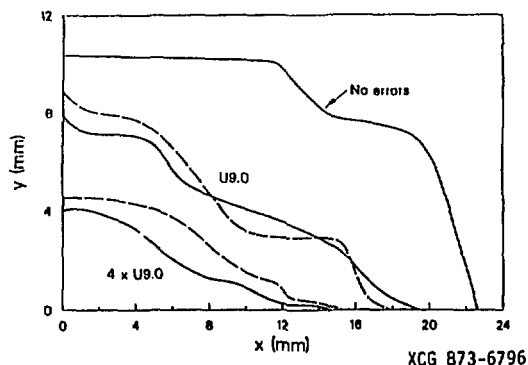


Fig. 7. Dynamic aperture with one and four undulators.

— "matched" solution
 - - - - - unmatched solution

It should be noted that the above studies have been carried out with the undulator set to its maximum field. Under these circumstances the equations we have used to describe the fields are no longer valid. A more accurate formulation of the small gap undulator field is required before proceeding further with these studies.

5. Summary and Conclusions

The introduction of magnetic field errors and nonlinearities into low emittance electron storage rings causes a significant reduction in the dynamic aperture. In the absence of insertion devices the effects are either acceptable or tractable, i.e., we can envisage operational methods of alleviating the problems. When we include wigglers and undulators the operation of the machine becomes much more complicated and we have not yet developed an algorithm for satisfying all the machine and user requirements simultaneously. These devices do, however, have one significant advantage over other error sources, i.e., they can be "turned off" (or at least their effects reduced) by opening up the gap or switching off the current. Thus, a possible operating scenario would be to turn off the insertion devices during the injection period when the aperture requirements are most stringent. This issue is one of the most serious outstanding problems confronting the next generation of synchrotron radiation sources, one that will have to be addressed by all laboratories hoping to operate such facilities.

6. References

- [1] 1-2 GeV Synchrotron Radiation Source Conceptual Design Report, LBL PUB-5172 Rev., July 1986.
- [2] A. Jackson, "The Magnet Lattice of the LBL 1-2 GeV Synchrotron Radiation Source," presented at this conference.
- [3] K. Halbach, private communication.

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